A Survey of Spectral Response Measurements for Photovoltaic Devices

**J. S. Hartman
M. A. Lind**

November 1981

**Prepared for
the Solar Energy Research Institute
under Contract DZ-0-9235
and the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$_____*; Microfiche \$3.00

*Pages	NTIS Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75
276-300	\$11.00

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SUMMARY

A survey of the photovoltaic community was conducted to ascertain the present state-of-the-art for PV spectral response measurements. Specific topics explored included measurement system designs, good and bad features of the systems, and problems encountered in the evaluation of specific cell structures and materials. The survey showed that most spectral response data are used in diagnostic analysis for the optimization of developmental solar cells. Measurement systems commonly utilize a chopped narrow-band source in conjunction with a constant bias illumination which simulates the ambient end use environment. Researchers emphasised the importance of bias illumination for all types of cells in order to minimize the effects of nonlinearities in cell response.

Not surprisingly single crystal silicon cells present the fewest measurement problems to the researcher and have been studied more thoroughly than any other type of solar cell. But, the accurate characterization of silicon cells is still difficult and laboratory intercomparison studies have yielded data scatter ranging from $\pm 5\%$ to $\pm 15\%$. The measurement experience with other types of cells is less extensive. The development of reliable data bases for some solar cells is complicated by problems of cell non-uniformity, environmental instability, nonlinearity, etc. Cascade cells present new problems associated with their structure (multiple cells in series) which are just beginning to be understood. In addition, the importance of many measurement parameters (spectral content of bias light, bias light intensity, bias voltage, chopping frequency, etc.) are not fully understood for most types of solar cells.

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INTRODUCTION

A laboratory survey was conducted to examine procedures and apparatus used to measure the spectral response of photovoltaic devices. The survey included laboratories with extensive experience in spectral response measurements and research groups with unique experience evaluating the performance of specific devices and materials. Visits at each facility included a discussion of measurement procedures, an examination of measurement apparatus, and a discussion of specific measurement problems associated with the devices being studied. Laboratories visited are listed in Table 1.

The diversity of materials and cell types in the PV development program complicates the measurement problem tremendously. The measurement of a) single and multiple junction cells, b) homojunction and heterojunction structures, c) one sun and concentrator devices, d) crystalline, polycrystalline, and amorphous materials construction, e) diffused junction and MIS devices, plus, f) the full range of specific materials employed is required. This diversity in the operating devices has led to the development of a wide variety of test apparatus and procedures used for materials and device characterization by the PV community.

In the past, the spectral response of photovoltaic devices has been measured primarily to provide diagnostic data that can be used to optimize cell performance. Fewer groups have examined the usefulness of spectral response data to predict the short circuit current of the test cell under alternate illumination spectra.⁽¹⁻⁴⁾ Consequently most researchers have not required a thorough examination of the problems and the limitations of spectral response measurements as applied to the prediction of cell performance. As a result, most spectral response apparatus has been designed to provide useful data on the cell under study but it may not provide useful data for all cell types. Specific examples will be cited in the equipment discussion to follow.

TABLE 1. Organizations Contacted for Survey
of Spectral Response Measurements

<u>Company</u>	<u>Location</u>
Arco Solar	Chatsworth, CA
Chevron Research	Richmond, CA
Exxon Research & Engineering Co.	Linden, NJ
Institute for Energy Conversion (University of Delaware)	Newark, DE
Jet Propulsion Laboratory	Pasadena, CA
Joint Center for Graduate Study (University of Washington)	Richland, WA
NASA Lewis Research Center	Cleveland, OH
National Bureau of Standards	Gaithersburg, MD
Princeton University	Princeton, NJ
RCA Laboratories	Princeton, NJ
Research Triangle Institute	Research Triangle Park, NC
Rockwell Science Center	Thousand Oaks, CA
Sandia National Laboratory	Albuquerque, NM
Solar Energy Research Institute	Golden, CO

Two laboratories which have studied the measurement procedures and problems in detail are NASA, Lewis Research Center (Cleveland, OH) and the National Bureau of Standards (Gaithersburg, MD). The NASA Lewis investigations began with photovoltaic cells for space applications and more recently have expanded to also include terrestrial applications. Their space cell work has required the development of accurate cell characterization procedures and equipment to predict end use performance for the cells.⁽⁵⁻⁷⁾ The importance of these procedures was enhanced by the high cost of test flights to provide actual performance data in the end use environment. The majority of their efforts have been directed at single crystal silicon cells although they also have considerable experience with GaAs, CdS, and several other emerging materials. They have investigated many questions that directly relate to measurement accuracy, reliability, and the range of applicability. Researchers at the National Bureau of Standards have investigated the performance of low current single crystal silicon photodetectors in an effort to develop more reliable radiometric standards. Their investigations have included the accurate measurement and detailed analysis of spectral response data and the calculation of the internal quantum efficiency of the photodetectors.⁽⁸⁻¹²⁾ Their measurement experience must be considered although the cell physics for their detectors may be different than found in solar cells due to differences in doping levels, junction depths, etc. Their combined efforts have added significantly to the current understanding of spectral response measurements and the potential problems associated with measurement apparatus.

The Jet Propulsion Laboratory also has extensive experience characterizing solar cells for both space and terrestrial applications. They have played a major role in cell characterization for the Low-cost Solar Array program (LSA). Their experience includes the investigation of equipment and measurement problems associated with the characterization of finished photovoltaic panels or modules.

The survey participants and the open literature clearly indicate that actual magnitude of the solar cell spectral response is affected by numerous internal processes and external stresses. Trapping effects, temperature effects and long-term environmental stability of the individual cells may cause large variations in spectral response. The

response of most solar cells is affected to some degree by the total amount of radiant flux falling on the cell or by the electrical bias imposed across the cell. The non-linearity in spectral response (and therefore effective quantum efficiency) is presumably caused by carrier traps or recombination centers that can in some cases be saturated or neutralized.

The temperature coefficients for the spectral response of most cell types are nonlinear. Both the sign and magnitude of the coefficient changes as a function of wavelength, therefore it is important to specify temperature for accurate measurements. The environmental stability of the cell is also important for accurate spectral response measurements. The cell history in the presence of moisture, trace gas impurities, UV photons, heat, etc., can affect the spectral response, sometimes drastically. The importance of these effects for most emerging material cells has not been adequately assessed.

The question must then be asked as to what the appropriate light and/or electrical bias conditions are for cell characterization. Should the cells be measured at short circuit current (I_{sc}), open circuit voltage (V_{oc}), current at maximum power (I_{mp}) or some other intermediate value of voltage or current?

GENERIC CELL MEASUREMENTS

Three types of spectral response measurements are commonly reported in the literature.

- 1) Spectral Responsivity - This is the simplest measurement to perform and data are reported in terms of "output current per unit incident optical power." Spectral responsivity curves can be prepared with a low impedance current meter, a calibrated optical power meter, and a knowledge of the optical source bandpass. A measurement system block diagram is shown in Figure 1. Data reduction with this system is based on the stored spectral irradiance distribution of the source as determined by an independent measurement.

FIGURE 1. System Block Diagram for Spectral Response Measurements Using a Stored Source Spectrum

This approach can be used only if the source exhibits good temporal stability for both its total irradiance and its spectral content. An alternate approach utilizes a characterized detector to monitor the narrowband source irradiance during the evaluation of the test cell. This provides simultaneous data on the source intensity and the test cell response and can be used with sources which exhibit long term drift. Spectral responsivity curves provide useful engineering data as the units allow the direct calculation of cell currents for a given irradiance distribution.

- 2) External Quantum Efficiency - This measurement utilizes the spectral responsivity data but requires the calculation of both the number of photons corresponding to the incident narrowband energy and the number of carriers corresponding to the measured current. The results are reported in terms of "carriers collected per incident photon." A measurement system block diagram is shown in Figure 2.
- 3) Internal Quantum Efficiency - This is the most complex spectral response type measurement as it requires a knowledge of the net energy absorbed in the solar cell from the narrowband illumination source. The net energy entering the cell from the narrowband source can be determined using two techniques. The first utilizes a measurement system similar to that shown in Figure 3. The energy absorbed by the semiconductor is determined by subtracting the reflected beam energy from the incident beam energy. This approach overestimates the energy absorbed in the active semiconductor by the amount of energy absorbed in the contact grid pattern. For high reflectance grid materials this is a second order correction and is commonly ignored. The second approach is based on a calculation of the fractional surface area obscured by the grid pattern and an assumption of uniform cell illumination. The absorbed energy is then calculated using the incident beam energy, the semiconductor reflectivity, and the fractional grid coverage. The full cell is generally illuminated in this system to avoid measurement to measurement changes caused by variations in the grid coverage at different locations on the cell. If the illumination is nonuniform

FIGURE 2. System Block Diagram for External Quantum Efficiency Measurements Using a Stored Source Spectrum

FIGURE 3. System Block Diagram for Internal Quantum Efficiency Measurements on Opaque Solar Cells Using a Stored Source Spectrum

across the cell, the effective grid coverage should be calculated using a weighting function determined from the illumination intensity pattern. If the source provides a uniform illumination pattern, the grid area determination can then limit the accuracy of the calculated internal quantum efficiency. The net energy entering the semiconductor is converted to the corresponding number of photons from the narrowband source. Results are reported as "carriers collected per photon absorbed in the cell." The internal quantum efficiency data are very useful for device analysis as they can be compared directly to a unity quantum efficiency curve. This can yield information on the importance of carrier loss mechanisms for photon energies greater than the band gap.

COMMON MEASUREMENT SYSTEMS

Commonly used measurement systems can be classified into two groups: 1) AC measurements using a chopped narrowband source or 2) DC measurements using an unchopped narrowband illumination source. The AC measurement technique facilitates the use of a constant intensity bias light source to simulate the ambient lighting conditions of the intended end use. The narrowband source intensity is generally much lower than that of the bias light source. Lock-in detection is utilized to determine the spectral response of the cell from the AC current component resulting from the chopped beam. This type of system can be used to evaluate the properties of cells which exhibit significant nonlinear behavior (e.g., the example seen in Figure 4).

The DC measurement system illuminates the test cell with only the unchopped narrowband illumination. The DC cell current then provides an indication of the cell spectral response in each narrowband spectral region examined. This type of system is much simpler to implement than the AC type system but it can only be used to measure cells which are known to have a linear response to the input illumination. Further, the cell must have a linear response over the full intensity range from that of the narrowband source to that of the end use if the data are to be

FIGURE 4. Relative Spectral Response Data for a CdS/Cu₂S Solar Cell With and Without AM1 Bias Illumination. Reference 13.

interpreted correctly. For concentrator cells, this could require cell linearity over a dynamic range of 100dB or more.

Monochrometers and filter wheels are commonly used as the wavelength selection elements in the source assembly. Schematics of alternate source arrangements using these devices are shown in Figures 5 and 6. Monochrometers allow a continuous change of incident wavelength. This can be very useful when a variety of cells are to be evaluated which are characterized by sharp response changes in different spectral regions. The flexibility to select any measurement wavelength will accommodate the necessary measurements. If a single grating monochrometer is used, it is generally necessary to use broadband color filters to prevent second order beams from reaching the sample. Monochrometers tend to suffer from low throughput, poor beam uniformity, and polarization effects (grating monochrometers). Filter wheels can provide higher intensity beams and better uniformity but lack flexibility in wavelength selection. The selection of narrowband color filters must insure that the filters are adequately blocked to prevent the transmission of light through undesired leakage sidebands characteristic of the thin film coating. Such leakage bands can totally invalidate the data if the filter passband is in a region of low cell response and the leakage passband is in a region of high cell response. Narrowband filters can also exhibit stability problems from extended exposure to UV radiation from the source and from environmental stress (humidity, temperature, etc.).

Commonly used source lamps include quartz halogen, quartz halogen with dichroic filter reflectors (to reduce IR content), and xenon arc lamps (both filtered and unfiltered). Quartz halogen lamps with dichroic filter reflectors are very common for providing bias illumination. The use of the dichroic filter reflectors reduce the infrared content of the beam by allowing much of the IR radiation to pass through the "reflector" while shorter wavelengths are reflected back in front of the lamp (Figure 7). The relative IR content in the beam is affected by the distance between the lamp and the test plane as the dichroic filter changes only the IR content of the reflected beam. The IR content of the direct beam is unaffected. This results in the relative IR content of the beam being higher near the lamp than it is at larger distances where the reflected beam dominates.

FIGURE 5. Schematic of a Source Assembly Based on a Monochrometer for Narrowband Wavelength Selection

FIGURE 6. Schematic of a Source Assembly Using a Filter Wheel for Narrowband Wavelength Selection

FIGURE 7. Spectral Irradiance Distributions for Quartz Halogen Bulbs with an Aluminized Reflector (—) and with a Dichroic Filter Reflector (----). Reference 14.

Rotating blade choppers are commonly used to provide beam modulation. Actual devices ranged from low cost, fixed frequency choppers to variable frequency choppers that allowed operation from 10 Hz to 5500 Hz. The variable frequency chopper allows the researcher to examine the effect of chopping frequency on the spectral response of the test cell. For some cells this can provide an indication of cell response limitations. It also allows the researcher to select an operating frequency that optimizes the system signal-to-noise ratio for the measurement. Care must be taken to select a chopper with frequency and phase stability specifications that will not degrade the overall measurement system performance. Beam chopping was also performed using mirrors mounted on the balanced members of a vibrating tuning fork. These commercial devices operate in a resonant mode with a limited range of frequency adjustment. Typical frequencies range from 30 Hz to 1000 Hz. The system observed during the survey utilized the beam during both portions of the tuning fork chopper cycle. When the blades (mirrors) were separated the beam was incident on the sample and when the blades were closed the beam was reflected to a reference cell which monitored the source output.

The measurement system designer must also consider the importance of temporal variations in the chopped beam for the specific solar cell under evaluation. Neither the rotating blade chopper or tuning fork chopper will provide an instantaneous on/off beam transition unless they chop the beam in a plane where it is effectively a point source. Both devices will chop a finite size beam in a manner that causes nonuniform temporal pattern for the surface illumination. The rotating blade chopper will be characterized by an illumination pattern that sweeps across the sample and provides an equal length of illumination time for each area of the sample exposed to the beam. The vibrating tuning fork on the other hand will provide a longer illumination time for the center of the illumination region than for the regions at the edge of the beam. This will tend to weight the signal from the center of the sample region more heavily than the signal from the edge regions. This can complicate data interpretation for samples with poor spatial uniformity.

The selection of a source design must also be based on the desired area of illumination and the illumination uniformity. These criteria must be established for both the bias light and the narrowband sources. Two basic approaches were encountered during the survey. The first is intended to provide the terminal characteristics of the complete cell and requires simultaneous illumination of the whole device. Reasonable beam uniformity is required to provide equal weighting of contributions from different regions of the cell. For example if the beam were concentrated at the center of the cell, the measured response would be dominated by properties of that region. The acceptable tolerance on beam uniformity is governed by the desired accuracy of the final results. The second approach is intended to provide the properties of the material in localized regions of the cell. Experiments to measure localized spectral response properties restrict the narrowband illumination to a small portion of the sample surface. Some systems provide a circular beam with a diameter of 150 μm or less for this measurement. This small narrowband beam can then be used in conjunction with bias illumination to measure the localized spectral response. Two approaches to bias illumination are used for these localized measurements.⁽¹⁵⁾ One approach illuminates the entire cell with the bias light while the other illuminates only a small region which includes the narrowband beam location. The "whole cell" configuration creates a large current contribution from the bias light which can significantly degrade the signal-to-noise ratio for the small chopped current signal. The use of small spot bias illumination will reduce the background current level and improve the signal-to-noise characteristics of the signal resulting from the narrowband illumination. However, device physics considerations may dictate which approach is best for studying a given cell. In either case, the spatial variations in the data are then related to material inhomogeneities within the cell. The small spot techniques have provided useful insights on developmental polycrystalline cells.

The voltage bias of the test cell during measurement is another system design consideration. Most single junction cells are measured at or near short circuit conditions. However, the cells will ultimately be used at the maximum power point in order to optimize system efficiency.

Such shifts in cell operating voltage can cause changes in the cell's response to the input illumination. The changes occur due to the modification of the junction width as a function of the cell bias voltage.⁽¹⁶⁾ This effect has been used successfully to study the location of recombination centers near the junction interface in developmental cells. The importance of the difference between the test and end use conditions has not been thoroughly evaluated. As an example, cascade cells require different bias conditions than single crystal homojunctions and will be discussed in the next section.

MEASUREMENT EXPERIENCE

Single Junction Cells (Non-Concentrator Applications)

Single crystal homojunction silicon solar cells have been studied more extensively than any other cell type. Researchers at the NASA Lewis Research Center have examined these cells for both space and terrestrial applications. Their studies have included the effects of solar cell linearity (bias light level), bias illumination spectral content, and the use of spectral response data to calculate I_{sc} . The NASA team has examined in detail many of the practical measurement problems which limit the accuracy of the spectral response data. The experimental system which has evolved from their studies can be used to record spectral response data accurate to within $\pm 5\%$. In general they conclude that cells should be tested under bias illumination levels consistent with the intended end use environment to avoid potential problems associated with cell nonlinearities. When this is not feasible it is necessary to carefully consider possible sources of error.

One approach is to examine the solar cell I-V curve under various bias illumination levels to determine the range of acceptable cell linearity before the spectral response data are recorded. Studies of the bias spectral content indicated that if the bias source does not provide an accurate simulation of the end use source, then the source should be relatively stronger at short wavelengths and weaker at the longer wavelengths (blue rich spectrum). This is due to the effectiveness of the shorter wavelength illumination for carrier generation and

surface trap neutralization while the longer wavelength components of the spectrum tend to contribute less to the cell current and still cause undesirable heating of the cell.

Specific cautions are necessary regarding the characterizations of the narrow band pass filters and beam power levels. As mentioned previously, the researcher using narrow band pass filters must be certain that they are adequately blocked outside the desired passband region. This is doubly important for researchers using arc lamps whose spectra contain numerous irradiance spikes which contain significant amounts of energy in a narrow wavelength interval (Figure 8). For the specific case of xenon compact arc lamps most of the large irradiance spikes occur at wavelengths between 800 nm and 1000 nm which is the region of maximum response for silicon solar cells. Spectral response data could contain large errors if the current is attributed only to the effect of the nominal passband illumination of the filter and does not take into account the sideband leakage of the filter. Care must be exercised in characterizing the narrowband source spectrum obtained from filters. In addition, experience has shown that standard detectors may not be linear over the energy ranges necessary to characterize the source spectrum. For example, some types of thermopile detectors are nonlinear when measuring microwatt power levels.

Researchers at the National Bureau of Standards have examined single crystal silicon photodiodes in an attempt to develop a reliable detector for radiometric measurements. Their measurements have been performed at a number of discrete wavelengths using laser sources.⁽¹⁸⁾ Bias illumination has not been used due to the relatively low power incident on the detector in most radiometric applications. The results of these studies have shown that the internal quantum efficiency of high quality silicon detectors can be accurately predicted over most of their spectral range from first principle calculations.⁽¹⁹⁾ In the course of these investigations they have also reported on instabilities in these photodetectors when exposed to UV illumination.⁽²⁰⁾

The NBS group has developed a radiometer package based on the same type of silicon photodiode studied in the preceeding paragraph.⁽²¹⁾

FIGURE 8. Spectral Distribution of Xenon Lamp Simulator. Reference 17.

These radiometers have served as the basis for an interlaboratory comparison of detector spectral response measurements. The preliminary results of this study indicate scatter in the data of roughly $\pm 5\%$ for visible wavelengths.⁽²²⁾ Significant contributions to the scatter in the data were attributed to wavelength errors and the rapid rate of change in the responsivity of silicon across the visible spectrum. Correction of these errors reduced the scatter to roughly -3% to $+4\%$ for the visible spectrum. This range of uncertainty is fairly consistent with the final results of similar comparison study conducted with vacuum photocells.⁽²³⁾ They found standard deviations of 2% for $450 \text{ nm} \leq \lambda \leq 620 \text{ nm}$ and of 5% at 390 nm and 690 nm. The similarity of the results for these two studies indicates the practical uncertainty in spectral response measurement capability of competent researchers using clearly outlined procedures. These values may represent practical uncertainty limits for spectral response data which might be obtainable for the PV community. However, an earlier interlaboratory intercomparison produced a response range of $\pm 12\%$ from the mean in the visible spectrum⁽²⁴⁾ and may more closely reflect the current level of expertise of the general PV community for routine measurements even on single crystal silicon cells.

The diffused junction single crystal silicon cells studied by NASA Lewis, JPL, and NBS present the fewest complications to the researcher measuring the spectral response. Yet the accurate characterization of these devices requires careful attention to many measurement details including both optical and electrical parameters.

Light bias effects for single crystal silicon cells are generally small ($<10\%$) and usually confined to the spectral region close to the band edge ($>800 \text{ nm}$). Temperature coefficients are also relatively small (negligible in the mid-visible [$\sim 500\text{--}600 \text{ nm}$] to a few percent per degree centigrade over most of the remaining spectral response region) for operation near room temperature.⁽²⁵⁾ The effects of electrical bias have not been fully explored, but are also expected to be relatively small.

Data from RCA⁽¹⁵⁾ and Exxon⁽¹⁶⁾ indicate that polycrystalline and amorphous MIS silicon cells are not as well behaved as single crystal cells. However, they are probably not as sensitive to light and electrical

bias as some of the common heterojunction cells such as the CdS/Cu₂S structures measured by the IEC group where the effects are very pronounced as illustrated earlier. Complete data for these materials systems is still lacking due largely to the early state of their development. There is also a wide variety of emerging material cells for which little or no data currently exists.

Single Junction Cells (Concentrator Applications)

Single junction cells (crystalline silicon and crystalline gallium arsenide) are being developed for concentrator applications under the leadership of Sandia National Laboratory (Albuquerque). These cells are intended for use at concentration ratios greater than 500X. This high illumination level presents several unique problems for the evaluation of spectral response. An easy and reliable technique to determine the actual optical concentration ratio over such a broad dynamic intensity range has not been proven. At the present time many concentration ratio values are based on the ratio of cell current under concentration conditions to the cell current under one sun illumination. This assumes the cell response is linear over the illumination range, but this has not been established experimentally. The use of black body detectors and calorimeters have also been used for these measurements with varying degrees of success to reduce the linearity uncertainty.

The question of device linearity is a primary concern for the measurement of the spectral response of concentrator cells. Recent studies have reported nonlinearities in the response of both single crystal silicon^(26,27) and gallium arsenide⁽²⁸⁾ concentrator cells. Present test procedures at SNLA determine the spectral response of the cells at low bias light levels (one sun or less) and with the narrowband illumination at levels far below those corresponding to one sun. One spectral response measurement system employs a commercial double beam spectrophotometer equipped with an integrating sphere. The test solar cell is mounted in the sample port of the integrating sphere. The sample channel of the spectrophotometer provides a measurement of light reflected by the sample. A simultaneous measurement is made of the cell photocurrent. The reference channel can be used to provide a constant

value for the incident energy using the servo-control on the monochrometer slit width. The system also can be operated with a fixed slit width if the reference beam is monitored to determine the energy incident on the sample. The cell current and cell reflectance data sets can be used together to calculate the spectral behavior of the internal quantum efficiency. In addition, the integrating sphere has been modified to allow the use of a bias light source during the measurement. The bias source is used to provide a current level than can saturate many of the traps in the crystalline cells but is not intense enough to simulate the end use concentrator applications.

Use of the spectrophotometer system operating with the slits under servo-control may present the researcher with several measurement questions that are not encountered in the other systems. When operating in this mode, the slit width is automatically controlled to maintain the signal level of the reference channel at a selected level. This allows compensation for the spectral properties of both the source irradiance and the detector response characteristics. However, changes in the slit width directly alter the beam bandwidth and depending on the design of the spectrophotometer system, may alter the beam geometry (height to width ratio and area). The changes in the beam bandwidth that affect the spectral purity of the beam, may not be critical for measuring devices with broad band spectral responses. On the otherhand, changes in the beam geometry may significantly affect the results. The fractional grid coverage may be altered as the beam dimensions change. Additional complications for data interpretation arise if the cell response is not uniform across the surface as the area sampled by the beam will also be changed by the slit width. The importance of these questions should be evaluated for the type of cells to be measured and for the specific spectrophotometer to be used in order to determine the impact on the measurement accuracy.

The acquisition of accurate reflectance data with the integrating sphere requires that the reference channel sample be selected with a knowledge of the test cell surface properties. If the test cell has a very smooth surface then a specular reference sample should be used. If the test cell has a textured surface that produces a great deal of scatter in the reflected beam, then a diffuse reference channel sample

should be used. Incorrect reference channel sample selection can cause significant measurement errors.

The concentrator cell measurement problem is difficult even with a system that would provide adequate bias light levels to simulate prototypic operating conditions. For example, assume a constant high intensity bias illumination and a chopped narrowband source are incident on the test cell. The DC current level from the cell will be orders of magnitude larger than encountered in one sun testing while the chopped current component probably will be fairly small. This large DC offset may shift the operating point for the lock-in amplifier beyond its dynamic reserve and degrade the instrument performance. Conventional lock-in amplifiers may not even be useful for such an application.

Cascade Cells (Concentrator Applications)

Cascade cells present several unique problems which result from their structure plus the usual problems already discussed for measuring concentrator cells. Cascade cells are prepared using multilayer stacks that electrically are two or more PV cells connected in series and separated by tunnel junctions. The tunnel junction is used to allow current injection from one PV junction to the next. The bandgap of the materials is selected to optimize the response of the top junction to short wavelength light and the bottom junction to longer wavelength light. In this manner the cascade cell is designed to respond more effectively to a larger portion of the solar irradiance spectrum than conventional single junction cells.⁽²⁹⁾ The series connection of the two junctions complicates the measurement of the cell spectral response current. In order to evaluate one of the junctions, the other must be turned on so it does not alter the properties of the junction under test. Procedures to allow this type of test have not been fully developed at this time and experiments are in progress to determine a reliable test procedure.

The approaches under investigation include the application of bias voltage and/or bias light to the cell under test. Researchers at the Rockwell Science Center have examined the effects of bias voltage on a cell with no bias illumination. Sample data are shown in Figures 9 and 10. The ability to change the bias voltage allows the researcher to adjust the cell operating conditions until the maximum power point is reached where the

FIGURE 9. Diagram of Three-Dimensional Spectral Photoresponse Contours for an AlGaAs/GaAs Cascade Solar Cell Under Various Applied Bias Voltages and Narrowband Illumination. No bias illumination was used. Reference 30.

FIGURE 10. Conventional Spectral Response Plot for AlGaAs/GaAs Cascade Solar Cell. Reference 31.

two junctions are operating in a balanced condition. At other bias voltages, one of the junctions will limit the total cell performance and the spectral response will be dominated by the performance of the limiting junction. Comparison of curves for two bias conditions in Figure 10 (0 volts and +1.61 volts) reveal the same general shape for the response curve for wavelengths between ~600 nm and 900 nm. This response corresponds to the lower junction in the cascade. However the response below 600 nm is very different for the two bias conditions. The response is low for the unbiased cell because the upper junction is reversed biased as a result of the zero terminal voltage and the forward bias on the lower junction. A bias voltage of +1.61 volts is sufficient to forward bias both junctions and a significant spectral response is seen from 400 nm to 900 nm. The complexity of the three dimensional response surface of Figure 9 clearly indicates the uniqueness of the cascade cells and the problems they present to the PV researcher.

Researchers at the Research Triangle Institute are examining the combined effects of bias light and bias voltage.⁽³²⁾ Data recorded using only a bias voltage exhibit a current response that peaks at one bias voltage (2.0 V on the cell discussed) with lower response at both higher and lower voltages. This results from matching the upper and lower cell response at the peak response voltage while one of the cells will limit the device performance at other voltages. This is consistent with the Rockwell discussions. The RTI bias light investigations include both white light (broadband) and filtered light (high pass and low pass) conditions.⁽³²⁾ The filtered bias light is selected to turn on the top junction and bottom junction independently.^(33,34) For the test cell discussed, these filters provided illumination from 380 to 600 nm and from 720 to 1200 nm. The results obtained with white light bias, filtered light bias, and optimized voltage bias (no light bias) are qualitatively similar but do exhibit significant differences in magnitude. Typical data are shown in Figure 11. The filtered bias light provides the largest response from both junctions. The use of white light bias yields the same response for the bottom junction (longer λ) but decreases the long wavelength response of the top junction. The voltage bias tests yielded a lower response than the filtered bias light but the

FIGURE 11. Spectral Response for AlGaAs/GaAs Cascade Cell Using Either Light or Voltage Bias Conditions. Curves show results for a DC bias voltage (—), white light bias (---), and a two-part filtered light bias, high-pass and low-pass (——). Reference 32.

wavelengths corresponding to major response features are essentially the same for the two data sets. Experimental investigation of these alternate approaches to cascade cell spectral response measurements is continuing at RTI in an effort to determine which method provides the most useful and reliable data.

Recently presented work has proposed a new approach to cascade cell spectral response measurements which may avoid the problems of internal junction bias voltages.⁽³⁵⁾ This measurement approach is based on analysis of the spectral response of the cell terminal voltage while the cell is operated at a constant current level. The data analysis assumes that terminal voltage changes caused by the narrowband beam striking the cell are a result of the electrical response of the junction which most effectively absorbs light at the incident wavelength. This effectively breaks the terminal voltage spectral response into a number of segments which equal the number of junctions in the cell. For the two junction cell whose characteristics were shown in Figure 10, the response at wavelengths longer than 620 nm would be attributed to the lower junction while response at shorter wavelengths would occur in the upper junction. Data reduction is then performed independently for the two wavelength regions.

Efforts are continuing at both Rockwell and RTI to clarify the implications of test conditions on the spectral response of cascade cells and to develop reliable measurement procedures for these cells.

GENERAL OBSERVATIONS AND CONCLUSIONS

- Spectral response measurements are generally used for materials development diagnostics. Measurement system sophistication is often limited to the level required for the specific material under test.
- Most researchers were not fully aware of the unique spectral response measurement problems facing researchers working with other material systems (i.e., no good sense of community overview). These problems include:

- strong light bias effects in some materials
 - environmental instability caused by one or more of the following
 - temperature
 - moisture
 - oxygen exposure
 - UV radiation
 - hysteresis effects in some materials following illumination
 - variability of the location of the response band in amorphous silicon
- Many researchers were not fully aware of possible nonlinear response effects (intensity related) in both their own materials and in the materials being studied by others. This applied both to groups working on one sun cells and concentrator cells.
 - No materials were felt to be sufficiently linear to allow the measurement of highly accurate spectral response without the use of bias illumination.
 - The differences between the spectra of a bias illumination source and the natural source are not too critical for the measurement of many types of solar cells. Rather, the more important quantity is often the total amount of radiant flux incident upon the cell.
 - The cell bias voltage is a measurement parameter that should be considered in a spectral response study. It is necessary to determine if the cell response differs significantly between short circuit and maximum power conditions.
 - Arguments were made for a simultaneous, whole cell evaluation and for a sequential examination of smaller regions of the cell depending on the planned end use for the data and the maturity of the specific cell technology.
 - When examined in its entirety, the spectral response measurement problem is far more complex than most PV researchers realized.

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ACKNOWLEDGEMENTS

The authors wish to thank the researchers and their organizations (Table 1) who added significantly to the findings of the community survey with their generous cooperation. Also they wish to thank P. Pierce and K. Emery of the Solar Energy Research Institute for their helpful suggestions and comments during performance of this study. This paper was prepared for the Solar Energy Research Institute under Related Services Agreement 300A01474 and the U.S. Department of Energy under Contract DE-AC06-76RL01830.

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Research Triangle Park,
NC 27709

Henry Brandhorst
NASA Lewis Research Center
2100 Brookpark Road
Cleveland, OH 44134

Dean Brooks
Research Triangle Institute
P.O. Box 12194
Research Triangle Park,
NC 27709

Ted Cannon
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

A.A. Churm
DOE Patent Division
9800 S. Cass Avenue
Argonne, IL 60439

Patricia Clover
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Henry Curtis
NASA Lewis Research Center
2100 Brookpark Road
Cleveland, OH 44134

Robert D'Aiello
RCA Laboratory
Princeton, NJ 08540

J.R. Davis
Westinghouse Research
1310 Beulah Road
Pittsburgh, PA 15235

Gil Downing
Jet Propulsion Lab
4800 Oak Grove Drive
Pasadena, CA 91109

5 Keith Emery
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Brian Faughnan
RCA Laboratory
Princeton, NJ 08540

Jon Geist
National Bureau of Standards
Washington, DC 20234

Russell Hart
NASA Lewis Research Center
2100 Brookpark Road
Cleveland, OH 44134

Steve Hogan
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

James Hutchby
Research Triangle Institute
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Research Triangle Park,
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Research Center
P.O. Box 1085
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Sandia National Laboratories
P.O. Box 5800
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Joint Center for Graduate Study
100 Sprout Road
Richland, WA 99352

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Wylie Laboratories
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ARCO Solar
20554 Plummer Street
Chatsworth, CA 91311

Sigurd Wagner
Princeton University
EECS Dept., B-422 Eng. Quad.
Princeton, NJ 08544

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Sandia National Laboratories
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